MATHEMATICAL MODEL OF THE HEAT TRANSFER PROCESS IN A RIBBED PIPE OF SPECIAL CONSTRUCTION

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DOI: https://doi.org/10.30525/978-9934-588-15-0-58

Abstract. One of the types of intensification of heat transfer in heat exchange equipment is the installation of ribs for heat exchange elements. The use of such developed surfaces allows to improve the parameters of heat transfer due to the turbulence of flows and significantly increase the specific heat transfer surface. This study is devoted to the development of a mathematical model of the process of heat transfer of a finned surface of a specific design. The effectiveness of the proposed rib design is confirmed by both experimental research and computer simulation in ANSYS. The mathematical models obtained adequately describe the heat transfer, both under forced and free convection. The proposed models take into account both the convective component of heat transfer and thermal radiation, which allows it to be used for selection, which operates over a wide range of temperatures. The thermal resistance of the heat exchange element takes into account the coefficient of thermal conductivity of the material and the geometric shape of the wall. Particular attention should be paid to the study of the effect of temperature deformations on the wall of the ribbed element. This is especially important in cases of large differences in coolant temperatures in the tube and between the tubes spaces, since the heat exchangers are subject to linear and volumetric deformation. In such situations, the heat exchanger element may lose its elastic equilibrium shape, which may lead to residual deformation and, in some cases, the destruction of structural members. Installation of ribs on heat-exchange elements must be carried out taking into account both the possible temperature deformations and in terms of structural features.

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All mathematical dependencies can be used in the calculations of heat exchange equipment with fins for predicting the parameters of the heat parameters and estimating the value of the heat flux. The reliability of the results is ensured by the correctness, completeness and adequacy of the physical assumptions in the formulation of the problems, the use of modern tools of mathematical and computer simulation, as well as the methods of statistical processing of experimental data, and is confirmed by the satisfactory conformity in comparing the results of the calculations with the obtained experiments.

1. Introduction

Modern biotechnological productions focused on the production of biologically active substances (BAS) with the use of biological agents require highly efficient equipment. As biological agents (BA), microorganisms, animal and plant cells and cellular components (cell organelles) are usually used.

The development of pharmaceutical biotechnology is focused on the exploitation of BA with the aim of obtaining active pharmaceutical ingredients (AFI), which are used as active substances in the composition of finished medicines (drugs).

Today, heat exchange processes are present in almost all technological processes of drug production and play a rather important role. Therefore, the intensification of heat exchange processes, the improvement and development of appropriate equipment is quite an urgent task.

Among various heat exchanger equipment shell and tube heat exchangers occupy their specific place and this is due to the fact that for the intensification of the heat transfer process, it is quite easy to increase the heat exchange area by the use of special ribbing on the tubes of the shell and tube heat exchanger [1, p. 201].

In heat exchange processes, shell and tube heat exchangers are quite efficient and easy to manufacture, as many years of practice in the use of these devices have shown. The designs of shell and tube heat exchangers are constantly being improved, the materials from which they are made are changing, which leads to a constant increase in the technical and economic parameters of the equipment [2, p. 570].

Studying the mechanisms of heat exchange processes and improving the structural elements of heat exchange equipment in order to increase the efficiency is a pressing problem today.

The subject of the research is the process of heat transfer, which are realized in the shell and tube heat exchanger of a special design with special ribbing.

The purpose of the work is to build a mathematical model of the heat transfer process and to improve the structural elements of the heat exchange equipment in order to intensify the heat transfer process and to improve the technical and economic performance of the equipment.

The intensification of heat transfer processes is quite interesting and challenging. When designing and improving heat exchange equipment, it is necessary to pay attention to a large number of various factors that can affect the overall technical implementation and individual design decisions. The efficiency of heat transfer equipment depends most on the temperature gradient and the heat transfer area. Usually, we cannot change the temperature gradient due to an existing process, whereas the heat exchange area can be developed in various ways. We have proposed a ribbing design that will be further used in the study.

Since this construction is new, the following issues need to be studied in the applied and fundamental aspects:

1) Development of a mathematical model of the heat transfer process through the proposed rib design for forced convection;

2) Development of a mathematical model of the heat transfer process through the proposed rib design for natural convection;

3) Analysis of the influence of fining parameters on the value of heat flux.

2. Formulation of the problem of theoretical research

The first stage in the development of a mathematical model of the system is the formulation of problems of theoretical research. Among the objectives of the theoretical study of the process of heat transfer through the ribbed tube of shell and tube heat exchanger of a special design were the following:

1. To propose a mathematical model for heat transfer through ribbing of a special design; the task is to solve the criterion equations that describe the transfer of thermal energy through the construction mentioned above;

This mathematical model is based mainly on the criterion equations describing the transfer of thermal energy through the ribbed surface.

2. Evaluation of the influence of process parameters on the amount of heat flow transmitted through the ribbed surface. To solve this problem, it is advisable to conduct a number of theoretical numerical experiments on the basis of the developed mathematical model.

In practice, it is convenient enough for these purposes to use the mathematical package MathCad, which makes it possible to automate a number of complex, often repetitive mathematical actions, to optimize iterative processes of graphical interpretations of functional dependencies.

3. Selection of optimal conditions for carrying out the process of heat transfer, based on the results of theoretical research. This task requires a comprehensive analytical approach to formulate conclusions on the entire volume of theoretical studies and is essentially the starting point for the practical implementation of the developed apparatus design.

3. Analysis of process features

One way to intensify heat transfer processes is to increase the heat transfer surface by using ribbing. The heating surface of the ribbed heat exchangers is made of tubes with transverse, longitudinal, wire, rod and other ribs.

The usage of finned heat exchange surfaces increases the heat exchanger's compactness, that is, the ratio of heat exchange area, to the volume it occupies. The use of ribbed heat exchangers makes sense when the heat transfer coefficient of one coolant is much less than the heat transfer coefficient of another coolant. Ribbing is usually performed on the side of a smaller coefficient of heat transfer [3, p. 415].

In Figure 1 the General view of the ribbed tube is shown.

In Figure 2 the cross-section of the ribbed tube with the proposed construction is shown.

This ribbing works as follows. During the operation of the heat exchanger, the fluid-coolant contacts the inner surface of the heat exchanger tube 1, washing its inner surface, and gives off heat energy with a coefficient of heat transfer $\alpha 1$ to the tube wall, which is made of a material with a high coefficient of thermal conductivity (copper, brass). In the wall of the tube 1 and the special rib section 2, heat transfer occurs due to the high thermal conductivity of the material. Further, thermal energy with a coefficient of heat transfer $\alpha 2$ from the surface of the wall of the tube 1 with special ribs 2 is given to the cold gas coolant (air), which is washed in the longitudinal direction the tubular element [1, p. 230].

In this design, the heat transfer is as follows:

Hot coolant (water) → tube wall → gap between rib section and tube wall → rib fin → cold coolant (air)

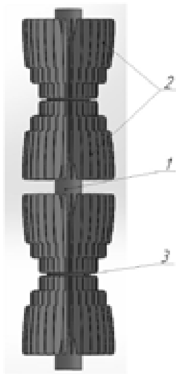

Figure 1 General view of the ribbed tube: 1 – tube, 2 – rib sections, 3 – fixing ring

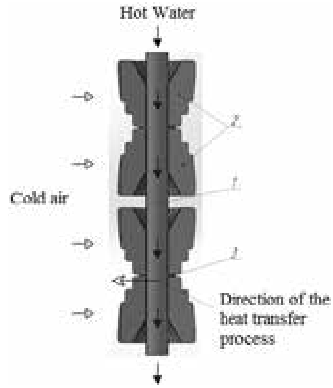

Figure 2 Cross-section of the tube with ribbing: 1 – tube, 2 – rib sections, 3 – fixing ring

In mathematical description of the process of heat transfer through this structure there are 4 thermal resistances, which affect the amount of heat flux transmitted through the fins design:

– thermal resistance of the tube wall;
– thermal resistance of the air gap;
– thermal resistance of ribbing;
– thermal resistance from the side of the washing air.

Therefore, when creating a mathematical model describing the process of heat transfer through a ribbed surface, it is necessary to take into account the influence of the above-mentioned thermal resistances on the heat flux.

The basis for the creation of this mathematical model are the following tasks:

1) Determination of the level of influence of technological gap on the amount of transmitted heat flow;

2) Finding the dependence of the heat flux value on the cold coolant (air) velocity washing the ribbing and on the temperature difference between hot and cold coolants;

3) Determination of the effect of the gap formed as a result of temperature deformations in the structural elements on the value of the transmitted heat flux.

4. Analysis of theoretical bases of heat transfer process

The increase in the heat transfer surface in the heat exchange equipment significantly intensifies the heat exchange process and, accordingly, increases the technical and economic performance of the equipment. A mathematical model of the process of heat transfer through the developed (ribbed) surface of heat exchange can be developed on the basis of a system of criteria equations by the methods of mathematical physics [4, p. 195].

Analysis of the theoretical foundations of heat transfer through the ribbed surface provides for the adoption of assumptions that in the future will develop a mathematical model and solve it for the particular case under consideration. At this point, it is necessary to describe the physical model of theoretical research as a functioning system, indicating the defining parameters of the system and their impact on it. Based on its features, it is possible to formulate geometric and physical conditions of uniqueness and set initial conditions [1, p. 220].

Geometric conditions of uniqueness. The system is a tube with special ribbing sections attached to it. The outer diameter of the pipe d_{out}, the inner diameter of the pipe d_{in}, the height of the rib section H, the average outer diameter of the rib section D_{out}, the thickness of the technological gap between the pipe and the rib section δ (Figure 3). Since the technological gap δ is rather small, it can be assumed that the heat flux section will have a tangential orientation, so it is convenient to choose a Cartesian coordinate system.

Physical conditions of uniqueness. The hot coolant (water) moves along the tube at the rate ω, the heat flow Q is transmitted through the tube wall and the technological gap to the edges. Cold coolant (air) moves at speed W, flushing the fins. The thermal energy in the ribbing section is propagated by convective heat transfer and radiation from the rib surface.

Initial conditions. At the initial time $\tau=0$ s, the fluids in the system are at rest (the velocities of the coolants are zero, $\omega=0$ m/s, $W=0$ m/s), there is no temperature gradient.

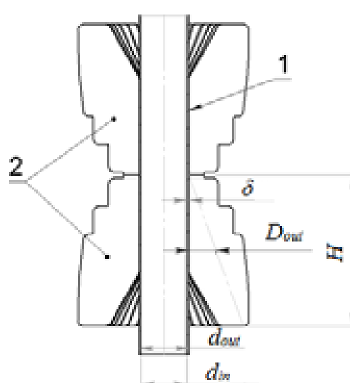

Figure 3. Research system: 1 – tube of heat exchanger, 2 – sections of special ribbing

The main process that takes place in the physical model is heat transfer. For a description of temperature distribution over the volume of the system commonly used grids method. This method allows you to determine the temperature at points of the system step by step, given the boundary conditions and laws of change of heat flow. This system can be considered with free and forced convection, which will determine the optimal mode of operation [5, p. 30].

5. Mathematical model of the heat transfer process for free convection

Grasshoff's criterion can be found by the formula:

$$Gr = \frac{g \cdot s^3}{\nu_{\text{B}}^2} \cdot \beta \cdot (t1 - t2). \tag{5.1}$$

Where β – coefficient of thermal expansion that is given by equation:

$$\beta = \frac{1}{273 + t2}.$$

Rayleigh criterion can find the formula, where Pr – Prandtl number for air:

$$Ra = Gr \cdot Pr. \tag{5.2}$$

Nusselt criterion equation for free convection:

$$Nu = 0.112 \cdot \left(\frac{s \cdot Ra}{L} \right)^{0.534} \cdot \left(1 - e^{-129 \cdot \frac{s}{L \cdot Ra}} \right)^{0.284}. \tag{5.3}$$

The heat transfer in this system with free convection is carried out by convective heat exchange between the ribbed surface and the cold coolant, and the radiation of heat from the ribs. Then the resulting heat transfer coefficient will have 2 components: the heat transfer coefficient for convective heat transfer and the heat transfer coefficient for radiation. Then the resulting heat transfer coefficient can be found by the formula:

$$\alpha = \alpha_{con} + \alpha_{rad}. \tag{5.4}$$

The coefficient of heat transfer in convective heat exchange can be found by the formula:

$$\alpha_{con} = \frac{Nu \cdot \lambda_a}{s}. \tag{5.5}$$

The coefficient of heat transfer during radiation can be found by the formula:

$$\alpha_{rad} = \varepsilon \cdot c_0 \cdot \frac{\left(\frac{273+t_1}{100}\right)^4 - \left(\frac{273+t_2}{100}\right)^4}{t_1 - t_2}. \tag{5.6}$$

The coefficient μ can be found by the formula [1, p. 211]:

$$\mu = \sqrt{\left(\frac{P \cdot \alpha}{F \cdot \lambda_m}\right)}. \tag{5.7}$$

The heat transfer parameter K can be found by the formula:

$$K = \lambda_m \cdot F \cdot \mu \cdot th(\mu \cdot L). \tag{5.8}$$

Where $th\,(\mu \cdot L)$ is a hyperbolic tangent from the product $\mu \cdot L$.

The heat flow from hot coolant (water) to cold coolant (air) can be found by the formula:

$$Q = \frac{(t_1 - t_2) \cdot L}{\frac{1}{\pi \cdot d_{in} \cdot \alpha_w} + \frac{\ln\left(\frac{d_{out}}{d_{in}}\right)}{2 \cdot \pi \cdot \lambda_m} + \frac{\ln\left(\frac{d_{out}+\delta}{d_{out}}\right)}{2 \cdot \pi \cdot \lambda_a} + \frac{1}{K \cdot z}}. \tag{5.9}$$

Where z is the number of ribs in the section.

The coefficient of heat transfer through the entire construction can be found using the formula:

$$K_e = \frac{Q}{(t_1 - t_2) \cdot L}. \tag{5.10}$$

Equation (5.9) can be considered as a mathematical model of heat transfer with free convection for the system under consideration. It characterizes the amount of heat flow that is transmitted through the whole structure.

6. Mathematical model of heat transfer process for forced convection

Determining size can be found by the formula:

$$d_D = \frac{4 \cdot F}{P}. \tag{6.1}$$

Where F is the cross-sectional area of the intercostal space, P is the perimeter of the cross-section of the intercostal space.

Reynolds criterion can be found by the formula:

$$Re = \frac{W \cdot d_D}{\nu_a}. \tag{6.2}$$

Where W is the rate of cold coolant (air).

Nusselt's criterion can be found by the formula:

$$Nu = 0.021 \cdot Re^{0.8} \cdot Pr^{0.43}. \tag{6.3}$$

Where Pr is the Prandtl criterion for air.

Since from the rib side heat transfer by radiation has virtually no effect on the amount of heat flow at high speeds of movement of the coolant, it can be neglected. Then the heat transfer coefficient for convective heat transfer can be found by the formula:

$$\alpha = \frac{Nu \cdot \lambda_a}{d_D}. \tag{6.4}$$

The coefficient μ can be found by the formula [1, p. 211]:

$$\mu = \sqrt{\left(\frac{P \cdot \alpha}{F \cdot \lambda_m}\right)}. \tag{6.5}$$

The heat transfer parameter K can be found by the formula:

$$\mathrm{K} = \lambda_m \cdot F \cdot \mu \cdot th\left(\mu \cdot L\right). \tag{6.6}$$

Where $th\ (\mu \cdot L)$ is a hyperbolic tangent from the product $\mu \cdot L$.

The heat flow from hot coolant (water) to cold coolant (air) can be found by the formula:

$$Q = \frac{\left(t_1 - t_2\right) \cdot L}{\dfrac{1}{\pi \cdot d_{in} \cdot \alpha_w} + \dfrac{\ln\left(\dfrac{d_{out}}{d_{in}}\right)}{2 \cdot \pi \cdot \lambda_m} + \dfrac{\ln\left(\dfrac{d_{out} + \delta}{d_{out}}\right)}{2 \cdot \pi \cdot \lambda_a} + \dfrac{1}{\mathrm{K} \cdot z}}. \tag{6.7}$$

Where z is the number of ribs in the section.

The coefficient of heat transfer through the entire construction can be found using the formula:

$$K_e = \frac{Q}{\left(t_1 - t_2\right) \cdot L}. \tag{6.8}$$

Equation (6.7) can be considered as a mathematical model of heat transfer with forced convection for the system under consideration. It characterizes the amount of heat flow that is transmitted through the whole structure.

7. A mathematical model of the heat transfer process for a non-ribbed surface with free convection

Grasshoff's criterion can be found by the formula:

$$Gr = \frac{g \cdot s^3}{\nu \text{B}^2} \cdot \beta \cdot (t1 - t2). \tag{7.1}$$

Where β – coefficient of thermal expansion that is given by equation:

$$\beta = \frac{1}{273 + t2}.$$

Rayleigh criterion can find the formula, where Pr – Prandtl number for air:

$$Ra = Gr \cdot Pr. \tag{7.2}$$

Nusselt criterion equation for free convection:

$$Nu = 0.112 \cdot \left(\frac{s \cdot Ra}{L} \right)^{0.534} \cdot \left(1 - e^{-129 \cdot \frac{s}{L \cdot Ra}} \right)^{0.284}. \tag{7.3}$$

The heat transfer in this system with free convection is carried out by convective heat exchange between the pipe surface and the cold coolant, and the radiation of heat from the pipe surface. Then the resulting heat transfer coefficient will have 2 components: the heat transfer coefficient for convective heat transfer and the heat transfer coefficient for radiation. Then the resulting heat transfer coefficient can be found by the formula:

$$\alpha = \alpha_{con} + \alpha_{rad}. \tag{7.4}$$

The coefficient of heat transfer in convective heat exchange can be found by the formula:

$$\alpha_{con} = \frac{Nu \cdot \lambda_a}{s}. \tag{7.5}$$

The coefficient of heat transfer during radiation can be found by the formula:

$$\alpha_{rad} = \varepsilon \cdot \text{c}_0 \cdot \frac{\left(\frac{273 + t_1}{100} \right)^4 - \left(\frac{273 + t_2}{100} \right)^4}{t_1 - t_2}. \tag{7.6}$$

The heat flow from hot coolant (water) to cold coolant (air) can be found by the formula:

$$Q = \frac{(t_1 - t_2) \cdot L}{\frac{1}{\pi \cdot d_{in} \cdot \alpha_w} + \frac{\ln\left(\frac{d_{out}}{d_{in}} \right)}{2 \cdot \pi \cdot \lambda_m} + \frac{1}{\pi \cdot d_{in} \cdot \alpha_{air}}}. \tag{7.7}$$

The coefficient of heat transfer through the entire construction can be found using the formula:

$$K_e = \frac{Q}{(t_1 - t_2) \cdot L}. \quad (7.8)$$

Equation (7.7) can be considered as a mathematical model of heat transfer for a non-finned surface with free convection for the system. It characterizes the heat flux that is transmitted through the whole structure.

8. Mathematical model of heat transfer process taking into account temperature deformations

Temperature deformation is a change in linear dimensions and body shape as its temperature changes. The coefficients of linear and volumetric temperature expansion are used to describe this phenomenon. They characterize the relative elongation of the linear dimensions (volume increase) of the medium with a temperature increase of 1ºC.

Under the influence of temperature, the linear dimensions of the parts increase, which can affect the technological gap between the tube and the rib section δ and, in turn, the magnitude of the heat flux transmitted through the whole structure [6, p.50].

Heat exchange tubes and fins are subjected to temperature deformation in the system. Since the fins are fixed to the support rings, which in turn are welded to the tube, the temperature deformation of the ribs will not affect the gap δ as shown at Figure 4.

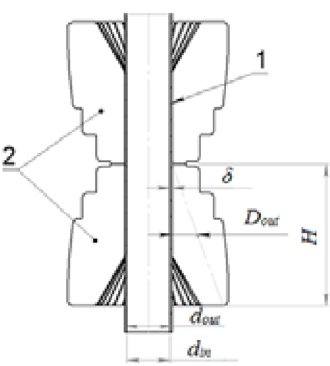

Figure 4 Calculation scheme: 1 – tube of heat exchanger, 2 – sections of special ribbing

The initial clearance for this system is δ_0=0.00014 m (sliding landing).

The temperature in the pipe wall changes according to the logarithmic law, then [1, p. 215]:

$$t(r) = \frac{\Delta T}{\ln\left(\frac{d_{out}}{d_{in}}\right)} \cdot \ln\left(\frac{d_{out}}{d_{in}}\right). \quad (8.1)$$

Where d_{out} is the outer diameter of the tube, d_{in} is the inner diameter of the tube, ΔT is the temperature difference.

The factor ε can be determined by the formula:

$$\varepsilon = \frac{2}{r_{out}^2 - r_{in}^2} \cdot \int_{r_{in}}^{r_{out}} \alpha_1 \cdot t(r) \cdot r_{out} dr. \quad (8.2)$$

Where $a_1 = 17,3 \cdot 10^{-6} \dfrac{1}{{}^\circ C}$ is the coefficient of linear temperature expansion for steel at 100ºC, r_{out} is the outer radius of the tube, r_{in} is the inner radius of the tube.

Integration constants can be defined by the formulas:

$$C1 = \frac{(1+\mu)(1-2\mu)}{1-\mu} \cdot \frac{1}{r_{out}^{\,2} - r_{in}^{\,2}} \cdot \int_{r_{in}}^{r_{out}} \alpha_1 \cdot t(r) \cdot r_{out} dr. \tag{8.3}$$

$$C2 = \frac{1+\mu}{1-\mu} \cdot \frac{r_{in}^{\,2}}{r_{out}^{\,2} - r_{in}^{\,2}} \cdot \int_{r_{in}}^{r_{out}} \alpha_1 \cdot t(r) \cdot r_{out} dr. \tag{8.4}$$

Where μ = 0,3 is the Poisson's ratio for steel.

The change in tube size due to temperature deformation can be determined by the formula:

$$U = \frac{1}{r_{out}} \cdot \frac{1+\mu}{1-\mu} \cdot \int_{r_{in}}^{r_{out}} \alpha_1 \cdot t(r) \cdot r_{out} dr + C1 \cdot r_{out} + \frac{C2}{r_{out}}. \tag{8.5}$$

The resulting gap can be found by the formula:

$$\delta_1 = \delta_0 - U. \tag{8.6}$$

This is the gap value and should be used for further calculations.

9. The results of the calculation

Mathematical modeling was performed for two values of the gap 0.00014 m and 0.000118 m. The results are presented in Table 1 and Table 2.

Table 1

The results of the calculation at the gap δ_0=0.00014 m

The system under consideration	t_w, °C	t_a, °C	K, $\frac{W}{{}^\circ C}$	K_e, $\frac{W}{m^2 \cdot K}$	Q, J
Ribbed with free convection	80	17.2	0.061	1.73	6.23
Ribbed with forced convection	80	17.2	0.936	15	53.9
Without ribbing	80	–	–	0.53	1.92

When analyzing tables 1 and table 2 it can be seen that the highest heat flux and the heat transfer coefficient are observed in the finned system during forced convection, which confirms the correctness of the created mathematical model. In second place, these are the free-convection fin system, and finally, the non-fin system has the worst performance.

Table 2

The results of the calculation at the gap δ_1=0.000118 m

The system under consideration	t_w, °C	t_a, °C	$K, \frac{W}{°C}$	$K_e, \frac{W}{m^2 \cdot K}$	Q, J
Ribbed with free convection	80	17,2	0,061	1,74	6,278
Ribbed with forced convection	80	17,2	0,936	15,92	57,33
Without ribbing	80	–	–	0,53	1,92

When comparing tables 1 and table 2 it can be seen that, taking into account the thermal deformations occurring in these systems, the actual gap δ1 between the pipe and the ribbing sections decreases (Figure 5), which in turn increases the heat flow and improves the heat transfer process as a whole.

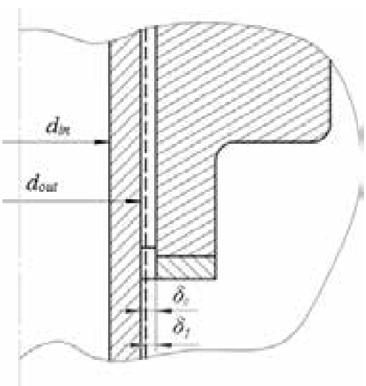

Figure 5. Scheme of influence of temperature deformations on the gap size

The graphs of the dependences *Q=f(ΔT)* (Fig. 6, Fig. 8) show that for the first iteration of the temperature change, as the temperature difference decreases, the heat flow for the free-convection finned system and for the non-finned system decreases, which is regular since the heat flow is directly proportional to the temperature difference.

The graph of dependence *Q=f(W)* (Figure 7) shows that as the rate of motion of the cold coolant (air) increases, the heat flow transmitted through the whole structure increases. As the coolant velocity increases, the Reynolds criterion increases, which in turn turbulates the flow, increases the heat transfer coefficient, and has a positive effect on the heat transfer process as a whole.

10. Conclusions

The mathematical model formulated adequately and describes the process of heat transfer in the considered systems, which is confirmed by the obtained results. The proposed model takes into account the precision of manufacturing and installation of ribbing elements on the heat exchanger

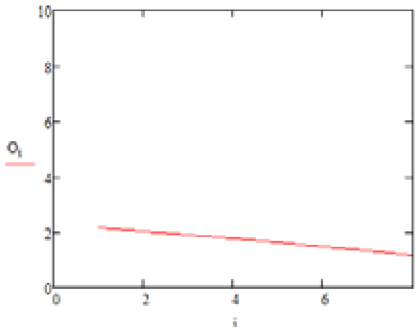

Figure 6. Inverse graph of the *Q* heat flux versus the temperature difference system Δ*T* for a free convection finned system

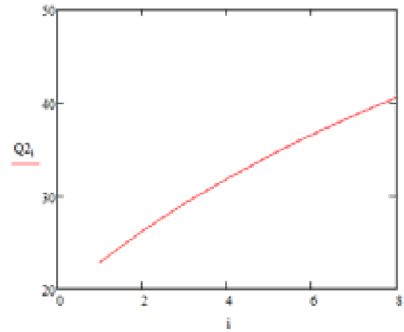

Figure 7. Graph of the dependence of the heat flux *Q* on the rate of cold coolant (air) *W* for a finned convection system

equipment (technological clearance and its influence on the amount of transmitted heat flow are taken into account). This model takes into account both free and forced convection, as well as the effect of temperature deformation on the size of the technological gap.

A number of dependencies have been obtained, which allow us to find the optimal operating conditions of these systems, which can greatly simplify the process of designing and calculating heat exchange equipment with finned surfaces.

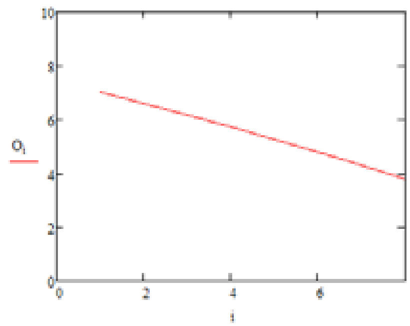

Figure 8. Inverse graph of *Q* heat flux versus temperature difference Δ*T* for a non-ribbed system

Based on the results of process modeling based on the developed mathematical model, it can be argued that one of the main factors that affect the efficiency of the fin and heat transfer process in general is the gap between the tube and the ribbed sections. When designing and calculating heat exchanger equipment with ribbed surfaces, it is necessary to take into account temperature deformations, which can both negatively and positively affect the efficiency of heat exchange processes. Also, the finning efficiency of hot and cold heat carriers (water and air, respectively) will affect the finning performance.

It can be concluded that the ribbing of the proposed configuration can be applied to significantly increase the area of heat exchange of equipment with tubular elements (eg shell and tube heat exchangers) provided there is sufficient space and conditions for the installation of rib sections.

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